AC 2012-4464: INTEGRATION OF A COMPUTATIONAL LAB SEQUENCE INTO A JUNIOR-LEVEL QUANTITATIVE PHYSIOLOGY COURSE

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Integration of a Computational Lab Sequence Into a Junior-Level Quantitative Physiology Course

Abstract

We have built a computational laboratory sequence within a junior-level quantitative physiology course within a biomedical engineering major. The course integrates mathematical, engineering, and biological perspectives into foundations of bioinstrumentation, models of physiology, and interfaces with physiological systems. We designed the computational labs to foster deeper and more facile understanding of core concepts as illustrated through dynamic system modeling. Here we assessed how students built this flexible facility, through assays of lab performance, practicum examination, and post-course survey. We conclude that the computational labs generated a framework for integrative and innovative understanding of course material.

Introduction

Quantitative Physiology I is a junior-level biomedical engineering (BME) course that requires students to integrate over foundational coursework in physics, biology, electrical and mechanical engineering, computer science, and technical writing. Students explore current and classic models of instrumentation, nerve, muscle, and biomechanics. Preceding 2004 the course was three credits consisting of a lecture- or lab-format; each week featured either traditional lectures or hands-on dry or wet laboratories. A consequence of the either-or structure was gap generation in lecture, leading to lack of continuity in substance and theme, and a lack of thought or energy preceding or following labs.

In 2005 the lead author expanded the course to four units. Several improvements were instituted simultaneously, including the incorporation of dedicated lab times, addition of lectures, organization of the course into coherent and interrelated modules, and expansion of the number of physical (hands-on) labs. The most substantive change, however, was the foundation of a computational lab (CL) sequence. The lead author designed these labs to complement the material in the rest of the course. Each CL featured a reading, a system to be modeled within Simulink (a graphical interface within MATLAB for modeling differential equations), and discussion questions to consider the output of the model and its relation to the core concept. With these labs we aspired for the students

- to build a deeper understanding of the core material
- to engage in the mathematical concepts underlying each model and connections across models
- to interactively explore how these models moved and evolved, to appreciate the dynamic nature of the models, and to understand dependence of output on input and on parameters
- to invest in their own flexible abilities, to enable themselves to generalize these skills to build and investigate models outside of the topics considered in the course.

Since we altered several of the course elements simultaneously, we cannot experimentally compare the particular comparative advantage of study with and without CLs. We will instead detail the course as we now teach it, the place of CLs within our instruction, and our investigation of evidence that CLs meet the aspirations listed above. Moreover the lead author has identified four central competencies to be built across the BME curriculum. All students build foundation in core disciplines, but atop that foundation students integrate across disciplines, innovate new ideas to real world problems, and disseminate their work to their communities and stakeholders. We will assay how students demonstrate these competencies in CLs.

Overall Goals of Quantitative Physiology I

One of the major goals of Quantitative Physiology is to integrate previously learned concepts in math, physical science, biology, and engineering into a rigorous investigation of the quantitative foundations of physiology. Prior to participating in the course, students in the Biomedical Engineering program are required to have taken courses in physiology, computer science or scientific computing, electric networks, and engineering mathematics. These concepts are meant to serve as building blocks not just for understanding more complex subjects of biomedical engineering but also for further explorations in the field. Hence, by the time that students are ready to take on Quantitative Physiology, they should be well equipped with the tools that they need, and QP serves as the instruction manual that demonstrates to students the more comprehensive usage of these tools. For example, throughout the course, we make explicit mathematical and electric engineering connections among previously learned course materials, such as how low and high pass filter behaviors from electrical circuits and signal processing captures behaviors in isometric/isotonic muscular force production. Furthermore, we also hope to show students the variety in the utilities of the tools they have obtained. The course spans multiple systems from sensory to neural to muscular, and from one system to the next, we explicitly show that many of their underlying concepts actually stem from similar engineering and mathematical ideas. For instance, we specifically show students that a dissipative element is a general concept that can be represented in form of a resistor for electrical systems, which can be used to model ionic gating in excitable membranes, but it can also be in the form of a damping element, such as the dashpot that is used to model the contraction and relaxation of skeletal muscle.

Moreover, in conjunction with achieving the integration purpose, another specific aim of this course is to encourage a more practical approach rather than a purely didactic approach. Through combination of lecture and laboratory exercises, we hope to build the analytical and numerical skills for evaluating existing biological models and developing new models based on experimental and computational experiment. For example, through simulating the Hodgkin-Huxley model for excitable membrane and a spring-dashpot model for skeletal muscles, the course offers exercises that allow students to observe how differential equations move through time so that the equations are transformed from their abstract mathematical form to a more concrete engineering form. The explicit usages of various analytical and numerical methods are shown across multiple settings in order to demonstrate to students the broad utility of their acquired knowledge and skills.

In conclusion, two encompassing aspirations inspired the materials in this course. One is to integrate what the students have learned before and to build, with the students, a more complete picture about the quantitative foundation of physiology. The other is to fortify and solidify various usages of analytical and numerical methods so that students are able to engage in independent scientific explorations.

Overview of Modules, Physical Labs, and Computational Labs

Currently, the first semester of Quantitative Physiology is divided into five modules: Signals, Systems, and Instrumentation; Peripheral Sense; Nerve; Skeletal Muscle; and Neural Prosthetics. Associated with each module are lectures, readings, one or more physical labs, one or more computational labs, and a homework set. The physiological systems covered include the brain, sensory functions, nerves, and skeletal muscle. Engineering concepts include signals and systems, sampling, filtering, circuit models, frequency analysis, transfer functions, and mathematical models such as the Hodgkin-Huxley equation and the Hill muscle model.

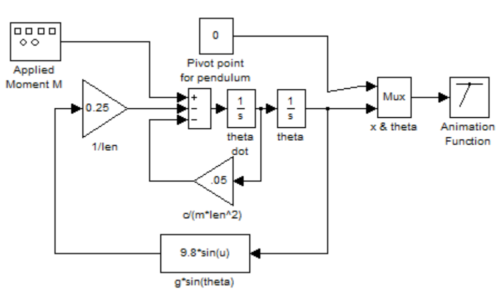
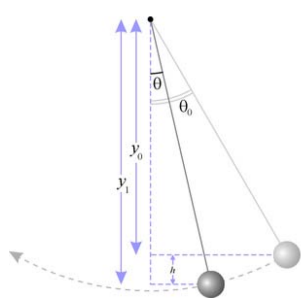
The Physical Labs, as taught in 2011

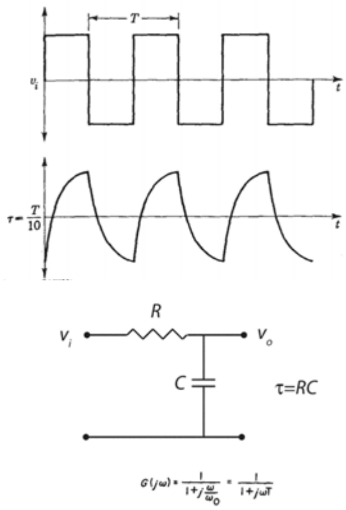
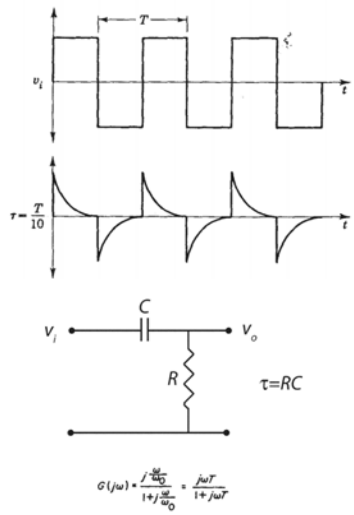
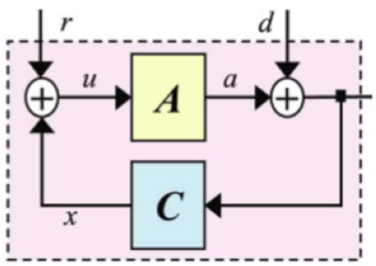
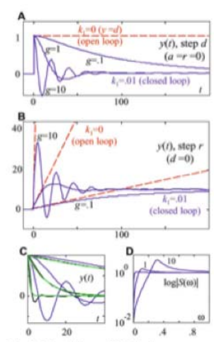
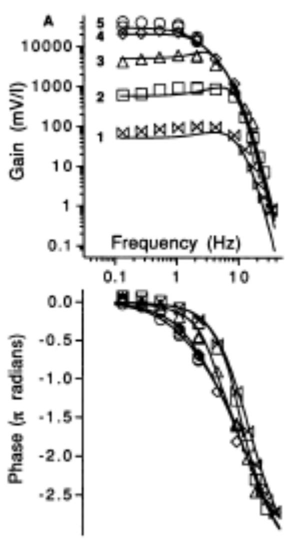
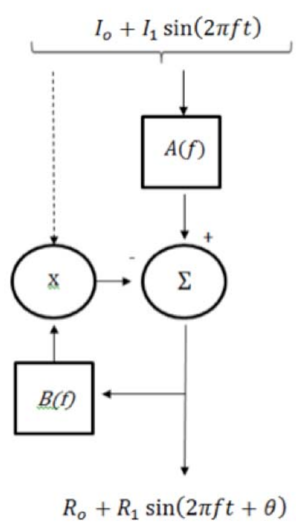
Six physical laboratory sessions are taught. The first physical lab introduces the equipment used to measure biological signals, and explores input impedance, common-mode rejection ratio, signal amplification, noise reduction, and filtering. The second physical lab introduces the data acquisition system used in the course, and covers A/D conversion, sampling rate, and frequency analysis. The third lab covers EEG signals, with evoked potentials, frequency analysis, and signal averaging.

The next two physical labs are dissection labs. The fourth lab studies compound action potentials in a frog sciatic nerve, including threshold voltage, biphasic and monophasic signals, conduction velocity, refractory periods, and strength-duration relationships. In the fifth lab, students dissect a sciatic nerve-gastrocnemius muscle preparation, and study muscle summation, fatigue, tetanus, length-tension relationships, and force-velocity relationships.

The last physical lab covers electromyography during static and dynamic muscle movement. This final lab also contains a student-designed lab component. Students are required to develop a hypothesis involving EMG, and design and execute a procedure to test their hypothesis.

The Computational Labs, as taught in 2011

 	CL1 asked students to model a simple pendulum with stiffness and damping. This lab introduced students to MATLAB and Simulink (Mathworks, Natick, MA), built basic programming skills, and introduced analysis of systems through alteration of parameters.

 	The first half of CL2 asked students to simulate RC and CR circuits in an initial exploration of low-pass and high-pass filters[1]. This investigation introduced analysis of systems through simultaneous alteration of parameters and inputs.
 	The second half of CL2 asked students to explore a toy model of feedback[2] that featured differential equations in both feedforward processing A and feedback processing C. The students observed the tradeoff between these processes, rejection of disturbance d, and retention of signal r.
 	CL3 asked students to simulate a classic model of a retina[3] and its discovery of an essential nonlinearity of transduction of light into retinal cell firing.

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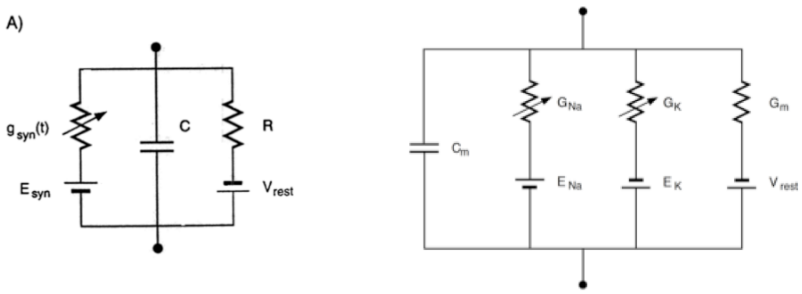
<td>
</td>
<td>In CL4 students investigated RC models of excitable membranes, including tunable synaptic conductances[4]. In CL5 students in teams implement individual components, then across teams integrate the full Hodgkin-Huxley model of action potential generation[5].</td>
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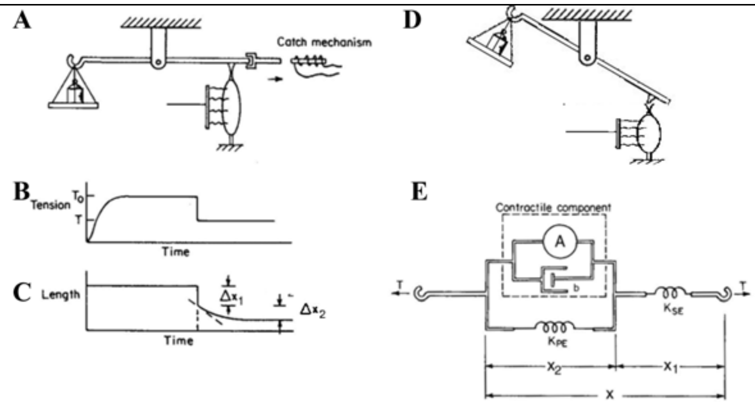
<td>
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<td>CL6 asked students to explore the isometric and isotonic behaviors of the Hill-type muscle model[6,7]. Student analysis of this lab formed one of our assays below.</td>
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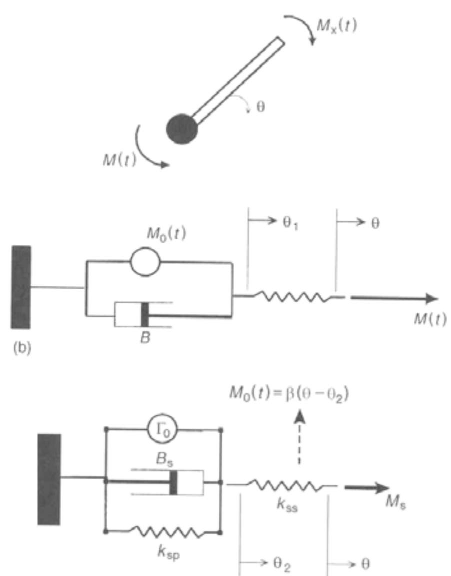
<td>
</td>
<td>After the six mentored CLs, students were tested with a practicum exam. Students modeled an open loop biomechanical coupling of a swinging limb with a simple muscle model, then closed the loop by adding muscle spindle feedback control[8].</td>
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The six computational labs thus provide an important framework connecting lecture topics and physical labs. CL1, CL2, and CL3 provide interactive investigations of topics in the Signals, Systems, and Instrumentation lecture module, portions of the Peripheral Sense module, and physical labs 1, 2, and 3. CL4 and CL5 directly illustrate concepts of the Nerve lecture module and the frog nerve dissection of physical lab 4. CL6 illustrates concepts from the Skeletal Muscle lectures and physical lab 5, and also provides a solid bridge back to earlier material of the Signals and Systems lectures of the first module.

Educational theoretical foundations to CL approach

Computational labs gave students the ability to revisit material presented in lecture and physical labs, so we expected students to more deeply understand this material through repetition. A unique advantage to the CL sequence, however, arises from a constructivist approach. According to a recent review by McDaniel and Wooldridge[9], "Constructivist teaching methods … differ from traditional education in that students are expected to take responsibility for their own learning in order to actively create knowledge structures." The sequence of CLs required students to build explicit models of instrumentation, control systems, sensation, bioelectricity, and biomechanics within a repeated Simulink environment, with explicit callbacks to previous labs. The students therefore found, and reported upon, connections in the mathematical models across topically different material. The laboratory environment encouraged students to discover these connections together; the write-ups demanded each student realize and disseminate these connections individually. Participation in the complete sequence provided students with constructivist opportunity, beyond more traditional lecture or paper-and-pencil, to consider and document their own developing understanding of mathematics and engineering within biology.

Assays from student product in CL6 and CL Practicum

In fall 2011, two teaching assistants, an educational support technician, and the lead author, all who have taught elements of this course evaluated the product of students to determine whether CLs aided students to develop integration, innovation, and dissemination skills within Quantitative Physiology I. The teaching assistants are BME graduate students who reviewed and graded all of the computational lab reports. The educational support technician holds a master's degree in biomedical engineering and supports the course faculty in the design and execution of computational and physical labs.

One assay we drew from the last computational lab, in which students modeled the Hill-type muscle model. This model has a contractile element and springs and dashpots to simulate the dependence of force generation on muscle length and velocity. We assigned students to simulate the model in two modes: isometric, in which the experimenter changes position and observes force; and isotonic, in which the experimenter changes force and observed position. As with all CLs, students examined the inputs and outputs and determined how system performance changed with inputs and parameters. We added an explicit requirement for students to integrate over the course to determine how the isometric and isotonic behavior recalled a previously modeled behavior. Students could find the strongest parallel in their models of low-pass and high-pass filters, as they pertained to instrumentation and processing within the auditory periphery.

Analysis by our educational support technician shows that 90% of the students attempted to answer this last, integrative question. Of these, 96% were able to correctly identify parallels to circuit models and filter design taught earlier in the course. A typical correct identification read:

> *The response behavior to a step input by the isometric and isotonic conditions are analagous to the step response behavior of a CR and a RC circuit, respectively (refer to Physical Lab 1 handout Figure 9). In other words,* ***the isometric stretch behaves as a high pass filter, whereas the isotonic stretch behaves as a low pass filter.*** *[bold in original] This reinforces the idea that the circuit models elements of electrical and*

mechanical systems are homologous since they are described by the same underlying differential equations.

Of those students who correctly identified a parallel, 70% further demonstrated a thorough understanding of the material through additional supporting statements, even though these statements were not explicitly requested in the laboratory assignment. An example of a more developed answer was:

The Hill muscle model explored under both isotonic and isometric conditions have similarities to previously examined concepts. Analogous to electrical circuits, the tension of the muscle is analogous to the "across" variable in a circuit. It acts like a force to cause a movement within the muscle. On the other hand, the length change is analogous to the "through" variable in a circuit. It is a measure of the movement of components within the muscle. Most notably, the model seems to show an exponential reaction to changes in the input similar to an RC circuit model. Although, there is an immediate change due to the series elastic element, the parallel element with a dampener and spring cannot react instantaneously. Similarly, the capacitor in a RC circuit cannot instantaneously respond to a change in voltage. This results in a more gradual effect that is observed in the exponential response. For an input of length change, we find there is a high-pass response in the change in tension which exhibits an exponential decay. Conversely, we find there is a low-pass response in the change in length which exhibits an exponential relaxation. The time constant, which influences how quickly the exponential change occurs, is determined by the product of the resistor and capacitor. Similarly, as the viscosity of the dampener is increased, the time constant to return to equilibrium increases.

A second assay measured performance on a CL practicum, an examination completed after the sequence of mentored CLs. The practicum asked students to demonstrate proficiency in a broad range of engineering concepts that they encountered earlier in the semester, such as comparison between open- and closed-loop behavior, in simulation of a novel model of sensory-motor reflex. The teaching assistant for CLs from 2010 acted as a naïve evaluator of performance on the (new to him) practicum administered in 2011. This TA developed metrics for how students displayed foundation, integration, innovation, and dissemination in this practicum.

The TA determined two aspects of the students' responses to grade for each of the four skills (foundation, integration, innovation, and dissemination), totaling eight criteria of individual student performance. Responses were marked as either 'correct', 'mostly accurate', or 'poor, or not present' for each criteria. In each of the four metrics, one criterion was explicitly requested in the practicum text, and the other was an optional but subject-relevant criterion to assess how many students go beyond what is asked of them to demonstrate their knowledge. For instance, in the 'Integration' category, students were explicitly asked to analyze the transient and steady state responses of the system, paying attention to rates of decay and the amplitude of oscillations; this skill was learned earlier in the semester in CL2. In addition, students could have characterized the system response as under-, critically, or over-damped, and as first or second order, even though language was not explicitly requested. An example of a well-developed answer for the Integration metric was:

In the second case, in which the muscle experiences gamma motoneuron control, the phenomenon observed is now a 3rd-order response (due to the inclusion of θ in (3)). Under conditions where the externally applied torque Mextis a step-input, the system attempts to compensate for the torque perturbation with some gain, or feedback efficacy, β. As shown in Figure 2, as β increases, the displacement of the system is damped with to an increasing degree. As β increases, the response characteristic transitions from an approximately low-pass overdamped response (purely exponential) to an underdamped response, whose response time constant increases with feedback. It implies that, as β increases, the system is able to adapt more readily to abrupt changes, but at a critical point (essentially where the response is critically damped), the system transitions into a mode where it adapts to quickly for its feedback to take full effect, especially when time delay is included in the system's dynamics. Thus, for β large, the muscle is able to resist an external perturbation more readily, but its overall time-domain response is unstable (oscillates heavily). In addition, the response appears to have a "shoulder" at very low onset after external perturbation, likely attributable to interactions from higher-order dynamics

An example of a 'mostly accurate' response captured the ideas of transient and steady-state responses, but did not express how the model parameters affect these responses:

From the graphs you can see that the steady state response is linear. In this model, the external torque was held constant as the stress reflex gain was varied. My model starts with an initial joint angle of 135 degrees. The transient response does not appear linear. There is a delay in the response of the muscle to change position. This could be because of the delay of neuronal transmission. In this closed loop model, there is a feedback loop telling the spindle organs the current position of the arm. We see that the angle of the arm increases with time. This makes sense if the arm is introduced to some external torque, the angle of the muscle would increase.

A poor example included neither the requested analysis of transient and steady state responses nor any additional integration with previous concepts. All four metrics were evaluated similarly, with one explicitly requested criterion and another for applying knowledge beyond what was requested. In their exam submissions, 77/85 students displayed foundations appropriate for the exam, and 81/85 exhibited explicit integration over previously encountered course material. Although the exam did not explicitly call for an innovative approach, 59/85 students exhibited innovation in their interrogation of the model. In their supporting statements, 82/85 students demonstrated proficiency in writing text that connected the graphical output of their model to concepts of quantitative physiology explored throughout the course.

Broader Measurement of Understanding of Course Concepts

A survey was sent to the students at the beginning of the course to determine their self-reported familiarity with specific topics and techniques that would be covered in the course. An identical survey was sent at the end of the course to measure the students' progress. Participation in the survey was voluntary and anonymous. Questions about proficiency ranged from the very specific (oscilloscopes, breadboards, MATLAB) to the more general (transfer functions, Fourier transforms).

This survey provided a measurement of progress in topics covered only in physical labs and in lecture compared to those covered in CLabs, physical labs, and lecture. For example, students reporting themselves to be "very proficient" or "somewhat proficient" on the subject of Fourier transforms rose from 49% at the beginning of the course to 84% at the end of the course. Fourier transforms are covered in lecture and are used in some of the physical labs. By contrast, a similar measurement on the subject of transfer functions rose from 46% very or somewhat proficient at the beginning of the course to 96% very or somewhat proficient at the end of the course. Transfer functions are covered in lecture, and are used in both physical and computational labs.

Conclusion

The addition of the computational labs (CLs) to the lectures and physical labs created a strong triumvirate of presentation across the physiological and engineering concepts of the course. In the first CLs, engineering students were introduced to two essential tools, MATLAB and Simulink. Subsequent CLs established a platform for students to study more complex and biologically-relevant systems such as nerve and muscle. By exploring these models in-silico students can perform experiments that would be impractical or impossible in physical labs. This deeper exploration reinforced important concepts and fostered a more meaningful physical lab experience. The computational labs provided a forum for revisiting early course concepts to strengthen understanding, as evidenced by the signals and systems connections measured from CL6. Finally, the computational labs assessed students' ability to apply their knowledge to novel problems, as measured by the practicum exam.

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